Radiological Consequences Of Severe Rail Accident Involving Spent Nuclear Fuel Shipments To Yucca Mountain: Hypothetical Baltimore Rail Tunnel Fire Involving SNF

By
Matthew Lamb and Marvin Resnikoff
Radioactive Waste Management Associates
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Radioactive Waste Management Associates
526 W. 26th Street #517
New York, NY 10001

Introduction

If the proposed Yucca Mountain waste repository opens, a large number of irradiated fuel and high-level waste shipments will converge in Nevada. Depending on a range of factors, hundreds to thousands of shipments will traverse Nevada annually for a period of 24 to 38 years.

A major impact of these shipments is the potential release of radioactive materials during a severe accident involving a long duration, high temperature fire. The Department of Energy's (DOE) Draft Environmental Statement (DEIS) for Yucca Mountain assumes that spent nuclear fuel (SNF) and high-level radioactive waste (HLW) shipping casks will be designed and certified to survive severe transportation accidents involving fires.

Under Nuclear Regulatory Commission (NRC) regulations, a cask must survive a 30-minute engulfing fire at 1475°F. However, technical analyses have identified a number of circumstances in which longer duration regulatory fires may cause failure of cask seals and fuel, as well as other preconditions for release of radioactive materials. If the regulatory fire (1475°F) burns for 2 to 8 hours, truck casks may fail massively, and at 20-22 hours even a large rail cask may fail. Higher temperatures or cask damage caused by an impact accident may cause failure and release in considerably shorter times. Moreover, none of the current or proposed truck casks have actually been subjected to a full-scale fire test.

Public and official concerns about the ability of SNF casks to survive severe fires have been heightened by an accident which recently occurred in the Howard Street tunnel on the CSX railroad in Baltimore, Maryland. The fire began on July 18, 2001, and continued for five days. According to news accounts, the peak fire temperature was estimated to be at least 1000°F to 1500°F, and the fire may have burned at or above these temperatures for several days.

The Baltimore tunnel fire represents an accident environment potentially comparable to the Modal Study's category 5 or category 6 accidents, which could result in a significant release of Cesium-134 and Cesium-137. Since current U.S. Department of Transportation (USDOT) regulations allow SNF casks to be shipped in mixed freight

trains, it is credible to assume that one or more SNF casks could have been part of such a train. Moreover, the accident occurred on a route identified in the DEIS as a potential corridor for rail shipments of SNF from the Calvert Cliffs reactor to Yucca Mountain.

The purpose of this report is to assess the health and economic consequences of a SNF rail accident patterned on the Baltimore tunnel fire. This report builds upon previous analyses prepared for the Nevada Agency for Nuclear Projects/Nuclear Waste Project Office (NANP/NWPO) by RWMA. The Baltimore consequence assessment discussed below employs the same general methodology as our previous assessments of severe truck and rail accidents at generic urban locations.

In Section 1 of this report we assemble background information on the July 2001 Baltimore rail tunnel fire, including details and the likely timeline of the Baltimore Tunnel fire, the response to the accident, and weather conditions during the accident. In order to estimate the health consequences of such an accident, we also collect information data on the tunnel and its normal operations, and Baltimore population density, land use, building types, and economic data. Our calculations are based on details of the accident as reported by the media and additional calls by RWMA, and may change when more information becomes available. The accident is being investigated by the National Transportation Safety Board.

In Section 2, we develop a credible scenario for an accident patterned on the actual fire but including a single rail cask of SNF. We estimate the likely damage to a spent fuel shipping cask exposed to these conditions, resulting in the prediction of release fractions and duration of release. The scenario is based on the assumption that a specific cask model is fully loaded with 10-year cooled PWR SNF. Most of the newer-generation shipping casks are certified to ship ten-year cooled fuel.

In Section 3, we assess the radiological consequences of the hypothetical accident. Using the RISKIND and HOTSPOT computer models, we estimate the 24-hour, one-year, and 50-year health effects and economic impacts in a format comparable to previous reports.

Section 1 Baltimore Tunnel Fire

Chronology

Extensive news coverage of the tunnel fire provided the data for a general timeline of the events of the Baltimore Tunnel Fire. A summary is provided below.

July 18, 2001: 3:04 pm:
Locomotives 100 yards south of tunnel entrance, traveling at 23 mph[1].

July 18, 3:07 pm
For some unidentified reason, emergency brakes on the CSX train are activated. The train is approximately 0.5 miles from the tunnel's northern end. "Soon, both ends of the tunnel would by cloaked by rolling black smoke… Black fumes were everywhere."[2]

July 18, 3:15 pm
The train crew shuts down the leading 2 locomotives, and then uncouples the third from the train cars. According to the crew, they try to radio the dispatcher, but are unable to.[3] Shortly after, the train engineer reaches the train master on his cell phone. The crew drives the engines out of the tunnel's north end to get away from fumes.

July 18, 3:25 pm
The engines leave the tunnel. The train crew reaches dispatchers and alerts them that the fumes were not dissipating. The crew notices the black smoke "pouring out of the tunnel."[4]

July 18, 4:15 pm
Fire department receives notification of the tunnel fire, 71 minutes after the onset of the accident.[5] Repeated attempts to enter the tunnel by the firefighters were unsuccessful.

July 18, approximately 5-6pm
The Coast Guard closed the Inner Harbor at approximately 5pm[6].

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[1] Fesperman, Dan. July 21, 2001. "Chronology: With a Rumble, Chaos." *Baltimore Sun.*
[2] *Ibid.*
[3] Radio communication may not have been possible within the tunnel.
[4] Fesperman, July 21, 2001.
[5] It is unclear why the train master did not immediately alert the fire department at 3:15 PM, rather than an hour later.
[6] Ettlin, David M. and Del Quentin. July 19, 2001. "Train Fire, Toxic Cargo Shut City." *Baltimore Sun.*

Players, employees, and fans are evacuated from Oriole Park at Camden Yards. "Joe Foss, vice chairman and chief operating officer of the Orioles, estimated that 2,500 to 5,000 fans were at or around the stadium, along with 2,000 employees, who were evacuated."[7] The Orioles were between games of a day-night doubleheader when the evacuation order was placed.

By the end of the day, most roads are closed within a two block-wide area (between Eutaw St. and Hopkins Place) extending 1.3 miles from Pratt Street near the south end of the tunnel to the Mount Royal Station at the north end of the tunnel is closed to traffic by local officials[8]. "All major highways and several smaller routes into Baltimore were closed."[9] The accident occurred during rush hour, resulting in severe gridlock throughout the area. Fire officials ordered businesses and residences near the tunnel to shut off air conditioning, shut windows, and stay indoors. These instructions are by TV and radio.

July 18, 5:45 pm
Baltimore's civil defense sirens are sounded.

July 18, 6:15 pm
Water main breaks at Lombard and Howard Streets, flooding much of downtown Baltimore above the tunnel. Power failures to approximately 1,200 businesses and residences results. Reduced or cut off water pressure as far south as Port Covington[10]. A 0.5 mi^2 section of Baltimore (bordered on the west and south by Martin Luther King Jr. Blvd and Hamburg Street, the east by Light Street and the north by Lombard Street is completely cordoned off[11]. The intersection of Lombard and Howard streets will be closed until September 4[12].

July 18, 10 pm
Firefighters attempt to enter the tunnel through the south end.

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[7] Rivera, John and Kimberly A.C. Wilson. July 19, 2001. "Baseball Fans and Commuters Held Hostage by Road Closings." *Baltimore Sun.*
[8] July 20, 2001. "Sun Graphic: A Closer Look at Downtown Traffic Disruptions." *Baltimore Sun.*
[9] Ettlin, David M. and Del Quentin. July 19, 2001. "Train Fire, Toxic Cargo Shut City." *Baltimore Sun.*
[10] *Ibid.*
[11] July 19, 2001. "Sun Graphic: Underground Spill Snarls City." *Baltimore Sun.*
[12] Associated Press. September 4, 2001. "Downtown Intersection Reopens. *Baltimore Sun.*

July 19
Workers begin removing cars from tunnel. The car containing tripropylene and other burning cars remain. Fires are still baking at 400°F, and smoke is still pouring from the north end[13]. Since the fire is now burning at the temperature of paper (~450°F), this suggests that tripropylene is no longer fueling the fire at this point.

July 21, 4:00 pm
Tripropylene tanker is removed from the tunnel. Other wreckage continues to burn.

July 22, early am
Firefighters remove last cars from tunnel.

Fire Characteristics

According to the Baltimore Sun, temperatures in the tunnel fire reached 1500°F, "hot enough to cause some of the CSX rail cars to glow, according to Battalion Chief Hector L. Torres, a Fire Department spokesman."[14] One firefighter described the glowing cars as "a deep orange, like a horseshoe just pulled out of the oven."[15] These descriptions are extremely useful because the color of glowing steel can be used to determine its temperature. For example, steel begins to glow at around 1000°F, with a dark red color, and begins to glow orange around 1650°F. Steel glows yellow at around 1825°F, and white around 2200°F[16]. The description of a "deep orange" suggests these rail cars were at temperatures near 1600°F or greater. The location of the fire was approximately 0.5 miles away from the South entrance to the 1.7-mile tunnel, making it very difficult to reach.

In addition to flammable tripropylene and various paper products, the train also contained corrosive acids. The train's cargo included propylene glycol, glacial acetic acid, fluorosilic acid, hydrochloric acid (next to the tripropylene car), ethyl hexyl phthalate, and pulpboard and paper products[17]. Hydrochloric acid is reported to have leaked, but there were no detectable releases of any airborne

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[13] Fesperman, July 21, 2001.
[14] Ettlin, D.M. July 20, 2001. "Burning Cars in Rail Tunnel Resist Control." *Baltimore Sun.*
[15] *Ibid.*
[16] Avallone, E.A. and T. Baumeister III, 1999. *Mark's Standard Handbook for Mechanical Engineers*. New York: McGraw-Hill. Table 4.2.25, pp. 4-57.
[17] Jones, Charles S. July 20, 2001. "Sun Graphic: A Car-by-Car Look at the CSX Train." *Baltimore Sun.*

hazardous materials in the smoke billowing from the tunnel ends. The tunnel fire burned for nearly three days.

Meteorological Conditions

Meteorological conditions at the time of the accident and subsequent fire were inferred from descriptions of the scene, photographs of the behavior of the smoke exiting the tunnel, and from data collected at the Baltimore-Washington International Airport (BWI), approximately 10 miles to the south of the accident location. Figures 1 and 2 present the frequency of wind speed and direction, respectively, measured at BWI during the time of the tunnel fire. These figures show the wind generally blowing towards the west-southwest at variable speeds, averaging about 3 m/s. Photographs of the black smoke billowing out of the tunnel show a “looping”-type distribution, characterized by an unstable atmosphere contributing to increased mixing. There was no recorded precipitation during the event.

Population Density and Demographics of Impacted Area

According to the 2000 U.S. Census, Baltimore city has a population of 651,154, a decrease of approximately 11.5% from 1990. High-density areas include sections directly west of the Howard Street Tunnel, such as Bolton Hill, Seton Hill, and Upton. In addition to the residential population density, the area near the Howard Street Tunnel has a significant employee and tourist population. Directly west of the Howard Street Tunnel is Oriole Park at Camden Yards, home of the Baltimore Orioles. Near the south entrance to the tunnel is PCINet Stadium, home of the Baltimore Ravens. Less than ½ mile east of the tunnel is Baltimore’s Inner Harbor, including the Baltimore Aquarium, restaurants, shops, and other attractions. The Baltimore Convention Center is due east of the southern end of the tunnel.

Howard Street Tunnel History and Operations

The Howard Street Tunnel was opened in 1895 by the Baltimore and Ohio railroad company so they could connect their eastern and western routes through Baltimore[18]. As it is currently operated, the tunnel is 1.7 miles long and varies from as little as 3 feet below the ground (near Camden Street) to almost 50 feet below ground (at Madison Street), giving the tunnel a 1.35 degree grade downward

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[18] Kelly, Jacques. July 8, 1996. “A Dank Relic Lies Below Howard Street Tunnel.” *Baltimore Sun*.

from south to north. Only one train may pass through at a time, and passenger trains do not use the tunnel.

On average, approximately 24-40 trains pass through the tunnel each day[19]. There are no restrictions on the cargo that can pass through the Howard Street Tunnel, and flammable materials such as propane are typically transported through it[20]. Therefore, there exists the potential for a more severe accident than the one occurring in July. The train line running through the tunnel is operated by the CSX Corporation, and after a short delay activities through it have resumed.

Section 2. Hypothetical SNF Accident

Assumptions for this Hypothetical Assessment

The purpose of this study is to estimate what would happen if a cask containing spent nuclear fuel were involved in the Baltimore tunnel fire. This is a credible scenario, since the current proposed rail route from the Calvert Cliffs reactor in Maryland to the proposed geologic repository at Yucca Mountain passes through Baltimore and likely through the Howard Street Tunnel, according to maps produced for the Yucca Mountain draft Environmental Impact Statement by the Department of Energy[21], which is included as Figure 3 of this report. Further, there is currently no requirement for rail shipments of spent nuclear fuel to be transported via exclusive-use train, creating the possibility for a spent nuclear fuel cask to be included among similar cargo, including flammable and hazardous materials.

Shipping Container Response to Fire Scenario

Since this accident involved a fairly slow-moving train, the severity of the accident can be taken to be a function of the fire severity and duration. As the timeline (Figure 4) suggests, the fire burned for more than 3 days, with temperatures as high as 1500°F. Current regulations require spent fuel shipping containers to withstand a 30-minute engulfing 1475°F fire. The tunnel fire has most

[19] Kelly, 1996, states that "most days, about 40 trains" go through the tunnel, while Myers and Dewar (see footnote 20) quote CSX, stating that "about 2 dozen trains" pass through the tunnel daily.
[20] Myers, Marcia and Heather Dewar. July 20, 2001. "Hazardous Materials Pass Daily – and No One Knows." *Baltimore Sun*.
[21] The maps are available online at: http://www.ymp.gov/timeline/eis/routes/routemaps.htm

assuredly exceeded these conditions.

In order to estimate the damage that might result from a shipping container exposed to the thermal conditions of the tunnel fire, it is necessary to estimate how quickly a cask could be expected to heat up in such an environment. The NRC has made some estimates about cask heating in an engulfing fire as part of NUREG/CR-6672[22].

According to NUREG/CR-6672, exposure to an 800°C (~1475°F) fire for prolonged periods of time has the following temperature thresholds[23]:

	Time (hours)	
Temperature	Steel-Lead-Steel	Monolithic Steel
350°C (662 °F)	1.69	2.37
750°C (1382 °F)	6.32	>11

Cask Internal Temperature as a function of time inside an engulfing 800°C Fire, according to NUREG/CR-6672, progresses as follows:

Time (min)	Cask Internal Surface Temperature, °C (°F)	
	Steel-Lead-Steel	Monolithic Steel
10	220 (428)	216 (421)
30	256 (493)	231 (448)
60	314 (597)	265 (509)
400	766 (1411)	562 (1044)

*(NUREG/CR-6672 assumes that, for longer-duration fires, the cask will eventually come into equilibrium with the fire.

The Modal Study[24] considers seal failure to begin at 500°F cask internal temperature. According to this document, it would take 1.35 hours to reach this point[25]. However, it is more applicable to consider the cask surface temperature when estimating seal failure temperatures, as was done in NUREG/CR-6672. Interpolating from the above table, this suggests that the rail cask seals would begin to fail after 31 (Steel-Lead-Steel) to 59 (monolithic steel) minutes inside

[22] Sprung, JL *et al, Reexamination of Spent Fuel Shipping Risks Estimates,* Sandia National Laboratories, NUREG/CR-6672, March 2000.
[23] NUREG/CR-6672, Tables 6.7 and 6.8.
[24] Fischer, LE, *et al, Shipping Container Response to Severe Highway and Rail Accident Conditions: Main Report (Technical Report)*, Lawrence Livermore National Laboratory, NUREG/CR-4829-v1,-v2, February 1987. Refered to as "The Modal Study" in this report.
[25] Modal Study at 6-39.

a 1475°F fire.

The next temperature plateau for the Modal Study is 600°F, which it estimates to be reached after 1.8 hours for a steel-lead-steel cask. This is also slightly slower than the NUREG/CR-6672 results. The lead inner shell of the Modal Study cask reaches 650°F after 2.6 hours[26], again slightly slower than estimated in NUREG/CR-6672. A category 4 accident requires cask mid-thickness temperatures to exceed 650°F, according to the Modal Study. Again interpolating from the above table, this plateau would be reached after 1.5 hours (steel-lead-steel) to 2.5 hours (monolithic steel).

Temperatures exceeding 1050°F are required for the most severe thermal classification in the Modal Study, which would occur after approximately 5.1 hours of exposure to the high-temperature fire[27]. Using the estimations in NUREG/CR-6672, this plateau would be reached in 4.2 hours (steel-lead-steel) to 6.7 hours (monolithic steel).

The Modal Study assumes that all fuel rods breach via creep rupture if the cask mid-thickness temperature exceeds 650°F[28]. NUREG/CR-6672 assumes that fuel rods breach via burst rupture if they reach temperatures greater than 750°C (1382°F). Using the estimations in NUREG/CR-6672, this plateau would be reached in 6.32 hours (steel-lead-steel) or greater than 11 hours (monolithic steel).

The fact that the fire in the Baltimore tunnel burned for 3 days or more at temperatures reaching at least 1500°F suggest that the thermal environment would be sufficient to reach all of these criteria. Evidence suggests that the fire burned at temperatures exceeding the regulatory fire for an extended period of time, perhaps 24 hours or more, since the presence of orange-hot rail cars suggests they reached temperatures of 1,200-1,800°F. Further, the tripropylene tanker car, which was believed to be the source material for the hot-burning fire, was completely empty when it was removed from the tunnel[29]. Therefore, we assume that a spent fuel cask engulfed in the tunnel fire would be a “worst case” accident scenario, a category 6 scenario under the classifications used in the Yucca Mountain DEIS.

[26] Modal Study at 7-22.
[27] *Ibid.*
[28] Modal Study at 8-10.
[29] Gibson, Gail and Marcia Myers. July 22, 2001. “Crews Remove Riskiest Cars.” *Baltimore Sun.*

Hypothetical Timeline of Spent Fuel Cask in Baltimore Tunnel

This section assumes that a spent fuel cask containing 24 PWR assemblies, 10-year cooled, from Calvert Cliffs, was involved in the Baltimore tunnel fire and situated next to the tripropylene car[30]. The following sequence of events uses the cask heat up assumptions from the Modal Study. To bound the expected cask response, we also present a timeline assuming the less conservative estimates of NUREG/CR-6672. For continuity, some of the entries are identical to those presented in Section 1 of this report, with new entries added to show the container response to the fire scenario.

A. Chronology: Steel-Lead-Steel Cask using Modal Study Thresholds

July 18, 2001: 3:04 pm:
Locomotives 100 yards south of tunnel entrance, traveling at 23 mph[31].

July 18, 3:07 pm
For some unidentified reason, emergency brakes on the CSX train are activated. The train is approximately 0.5 miles from the tunnel's northern end. "Soon, both ends of the tunnel would by cloaked by rolling black smoke… Black fumes were everywhere."[32] It has been speculated that sparks, either from the emergency brakes or from a derailment, ignited the tripropylene tanker car. We assume that a 1500°F fire begins at this time.

July 18, 4:27 pm
The cask mid-thickness temperature of a steel-lead-steel cask reaches 500°F, at which point the cask seals begin to fail. Radioactive release may begin at this time.

July 18, 4:55 pm
The cask mid-thickness temperature of a steel-lead-steel cask reaches 600°F, at which point the cask seals have completely failed.

[30] Calvert Cliffs fuel properties taken from: "Energy Information Administration: Detailed United States Spent Nuclear Fuel Data as of December 31, 1998." Office of Civilian Radioactive Waste Management, Department of Energy. http://www.eia.doe.gov/cneaf/nuclear/spent_fuel/ussnfdata.html.
[31] Fesperman, Dan. July 21, 2001. "Chronology: With a Rumble, Chaos." *Baltimore Sun.*
[32] *Ibid.*

July 18, 5:43 pm
The cask mid-thickness temperature of a steel-lead-steel cask reaches 650°F. Fuel rods begin to fail by creep rupture. The release estimates in the Modal Study assume that all rods fail at temperatures greater than 650°F. The radioactive release intensifies.

July 18, 8:13 pm
The cask mid-thickness temperature of a steel-lead-steel cask reaches 1050°F, the most severe thermal classification in the Modal Study. More radioactive material is released as rods depressurize.

B. Chronology: Monolithic Steel Cask using NUREG/CR-6672 Thresholds

July 18, 2001: 3:04 pm:
Locomotives 100 yards south of tunnel entrance, traveling at 23 mph[33].

July 18, 3:07 pm
For some unidentified reason, emergency brakes on the CSX train are activated. The train is approximately 0.5 miles from the tunnel's northern end. "Soon, both ends of the tunnel would by cloaked by rolling black smoke… Black fumes were everywhere."[34]

July 18, 5:29 pm
The cask mid-thickness temperature of a monolithic steel rail cask reaches 350°C, at which point the cask seals begin to degrade. Radioactive release may begin at this time.

July 18, 6:30 pm
The cask mid-thickness temperature of a monolithic steel rail cask reaches 400°C, at which point the cask seals are completely degraded.

July 19, 3:34 am
The cask mid-thickness temperature reaches 750°C, at which

[33] Fesperman, Dan. July 21, 2001. "Chronology: With a Rumble, Chaos." *Baltimore Sun.*
[34] *Ibid.*

point (according to NUREG/CR-6672) the fuel rods fail by burst rupture.

The temperature profile of each of the casks and the important milestones are shown in Figures 4 and 5. In our opinion the fire burned long enough and hot enough to reach the maximum threshold whether we use the assumptions in the Modal Study or NUREG/CR-6672.

Section 3. Consequences of a SNF Accident

Simplified Model of Release

We predict that the highest temperature thresholds will have been reached between 5 and 12.5 hours after the initiation of the fire, depending on the cask type. For a simplified representation of what could have happened if a spent fuel cask was involved in the tunnel fire, we treat it as a puff release being released equally from the North and South ends of the tunnel. We take the wind speed to be the average occurring over the duration of the fire (winds blowing to the west-southwest at 3 m/s, stability class A assumed from photographs of the looping plume exiting the tunnel). We use the Modal Study release estimates for a category 6 accident, with the correction for cesium gap inventory discussed in the appendix. Because the accident takes place in a tunnel, we assume that 50% of all particulates plate-out on nearby surfaces and are therefore not part of the airborne release estimate.

Using these assumptions and demographic data from the 1990 U.S. Census, we can estimate the number of people exposed and the extent of exposure. Because the plume emanating from the South entrance of the tunnel travels directly over the PCINet Stadium, home of the, we calculate 2 accident scenarios: one assuming the accident took place on July 18, 2001, and other assuming an accident in the Fall, during a sold-out Baltimore Ravens football game. Further, data from the 1990 Census was used because it was much more detailed than that currently available from the 2000 Census. Because of this, we also included a scenario that discounted the population by 11.5% (the average decrease in population in Baltimore City from 1990 to 2000).[35]

[35] It is also possible that the present renaissance of the Baltimore downtown and waterfront area may give rise to a population increase in future years. This has not been taken into account for this study

Figures 6 and 7 show the acute dose isopleths due to the postulated accident conditions discussed above. Figure 6 is an overview of the acute dose isopleths (from 10 mrem to 5 rem), with the affected areas of Baltimore separated by Zip Code. Figure 7 shows a close-up view of the Howard Street Tunnel, Camden Yards, and PCINet Stadium. Figure 8 presents the 1-year long-term dose isopleths, while Figure 9 shows the 50-year long-term isopleths, both assuming no cleanup, inderdiction, or relocation. Figure 10 shows the ground contamination isopleths, in units of $\mu Ci/m^2$.

Estimated Health Consequences of Accident

Table 1, below, presents the results of the differing scenarios for short-term (24-hour) exposure, 1-year exposure, and 50-year exposure. It is important to note that the exposure estimates assume no evacuation or cleanup, in order to provide a bounding result.

Table 1: Results: Evaluation of Baltimore Tunnel Fire with Hypothetical Spent Fuel Cask

	Exposure to Baltimore Residents	Exposure at PCINet Stadium if filled to capacity during incident
Affected Population, 1990 (2000)	390,388 (345,493)	69,400
Area with acute dose of at least 10 mrem	11.0 km^2	11.0 km^2
Max. Downwind Distance of 10 mrem acute dose plume	6.8 km	6.8 km
Area with acute dose of at least 1 mrem	173 km^2	173 km^2
Max. Downwind Distance of 1 mrem acute dose plume	38.7 km	38.7 km
Acute Population Dose, 1990 (2000) [person-rem]	17,509 (15,495)	38,170
Range of Estimated Excess Latent Cancer Fatalities from Acute Dose, 1990 (2000)	9-56 (8-50)	19-122
1-Year Population Dose, 1990 (2000) [person-rem]	495,498 (438,516)	--
Range of Estimated Latent Cancer Fatalities from 1-year Dose, 1990 (2000)	248-1,586 (219-1,403)	--
50-Year Population Dose, 1990 (2000) [person-rem]	9,944,974 (8,801,302)	--
Range of Estimated Latent Cancer Fatalities from 50-year Dose	4,972-31,824 (4,401-28,164)	--

These values could be significantly curbed if an appropriate evacuation and decontamination took place. The fact that this scenario involves cask degradation due to a high-temperature fire allows for some warning time between the accident and significant releases. The first release of radioactive material could begin when the cask seals degrade, which we have estimated to occur approximately 1.3 hours after the onset of the fire for a steel-lead-steel cask, and 2.4 hours after the onset for a monolithic rail cask. However, in the particular case of the Baltimore tunnel accident, the

fire department was not notified until over an hour after the accident, and the city's warning sirens weren't sounded until 2.5 hours after the accident. This may not have left enough time for officials to effectively evacuate the areas closest to the accident before the release began. We have not investigated whether the City of Baltimore has a plan in place to handle a tunnel fire involving radioactive materials, and whether emergency personnel are trained through educational programs and drills, and are equipped, to handle such an emergency.

It appears that some emergency measures were performed well, while others were not. Ordering the cut-off of air-conditioners via mass media was a useful step, but it is not clear whether the order was effective. Not all building supervisors are watching television at 5 – 6 PM, or are on the building premises at that hour. The use of the civil defense warning sirens, tested every Monday for the past 20 years, was intended to alert people so they would check the radio or television for further information, but this was confusing. In fact, many telephone calls were placed to City Hall asking what the sirens meant[36]. Additionally, the sirens were not sounded until 5:45pm, more than 2.5 hours after the accident. Further, since the central downtown area was blocked off, evacuation could not have occurred in the most efficient manner. Clearly, people should be kept out of a contaminated area, and not track contamination from a contaminated area to a clean area, but blocking major thoroughfares also impedes the evacuation process. The case of a fire-only accident involving spent fuel gives some time between the onset of the fire and the rupture of fuel rods leading to the most significant release of radioactivity, most likely long enough to evacuate the area immediately surrounding the tunnel where the highest exposures would be seen. This action would significantly reduce the health consequences of such an accident. In order to reduce long-term dose, significant decontamination of the effected areas would be required, along with the likely relocation of a large number of households and businesses most affected. This would result in the virtual crippling of the southwest side of Baltimore. Our previous studies have estimated the economic consequences of rail accidents involving spent nuclear fuel in an urban location in the hundreds of billions of dollars, far more than available under Price-Anderson nuclear liability insurance. A trade-off may take place between continual long-term radiation exposures and dollar costs to clean up the affected area. Regardless, the scenario involving a spent nuclear fuel cask in a situation similar

[36] Schoettler, Carl. July 20, 2001. "Duck and Cover? No, find the Remote" *Baltimore Sun*.

to the Baltimore tunnel fire would be disastrous.

Estimated Economic Consequences of Decontamination and Cleanup

As has been previously discussed, many of the latent effects of such an accident could be prevented with proper evacuation and decontamination. There is, however, an enormous monetary expense associated with this proper decontamination.

Previous estimates of the duration of decontamination following a plutonium dispersal accident were made by Chanin and Murfin[37]. Their study estimated the activities likely to be involved in the decontamination of an accident involving the dispersal of plutonium. Although the radioactive material they studied is different than the spent fuel accidents discussed in this study, the methodology and conclusions used by Chanin and Murfin to estimate decontamination costs are directly useful. For example, their study estimates the cost of decontamination as a function of the level of cleanup required to achieve an acceptable level. The cleanup level is assigned a decontamination factor (DF) of 1, meaning that no cleanup is needed to meet the criteria. Areas contaminated to up to 5 times the cleanup level are considered to be lightly contaminated, areas with levels between 5 and 10 times the cleanup level are considered to be moderately contaminated, and areas exceeding 10 times the cleanup level are considered to be heavily contaminated. For each level (light, moderate, heavy), certain cleanup assumptions are made and a cost is estimated for both rural and urban environments. Further, the costs associated with cleanup assumed in the Chanin and Murfin study are relatively non-specific with respect to the type of contamination. For example, they estimate the cost involved with scrubbing sidewalks and buildings in order to remove contamination, which would occur in the aftermath of a spent fuel accident involving the release of radioactive particulates. Therefore, we use these criteria to estimate cleanup costs. In addition, we use the estimates made by Chanin and Murfin with regard to the duration of decontamination, applying the contaminated areas estimated here to their values.

In order to estimate the extent of contamination and the required cleanup, an estimate of the acceptable cleanup level is required. While the actual cleanup criteria adopted after a severe

[37] Chanin, DI and WB Murfin, "Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents," SAND96-0957, May 1996.

accident may ultimately be dictated by local concerns, Price-Anderson insurance and Congressional activity, the EPA's protective action guide (PAG) states that relocation is warranted when the first year dose will exceed 2 rem. Any yearly dose after the first year should not exceed 0.5 rem, and a cumulative total of 5 rem is set as the limit for a 50-year exposure period. Using a 50-year dose of 5 rem as the cleanup criteria, our analysis estimates that more than 50 km^2 would require decontamination. The study by Chanin and Murfin estimated that it would cost $394 million per square kilometer to remediate a heavily contaminated area (greater than 10 times the cleanup criteria), $182 million per km^2 to remediate a moderately contaminated area (between 5 and 10 times the cleanup criteria), and $128 million per km^2 to remediate a lightly contaminated area (between 1 and 5 times the cleanup criteria).[38]

Using the EPA's PAG and the cost estimates made in the Chanin and Murfin study, we estimate the cleanup cost following the hypothetical Baltimore Tunnel accident. Figure 11 shows isopleths of interest (at the cleanup level, at 5 times the cleanup level, and at 10 times the cleanup level). Table 2, below, presents the results of this estimation.

Table 2: Decontamination Cost Estimates: Baltimore Tunnel Fire Spent Fuel Accident

Area heavily contaminated (km^2)	9.9
Area moderately contaminated (km^2)	10
Area lightly contaminated (km^2)	62.4
Cost/km^2, heavy contamination[38]	$394,604,748
Cost/km^2, moderate contamination[38]	$182,592,165
Cost/km^2, light contamination[38]	$128,263,609
Total Cleanup Costs	$13.7 billion

These cleanup cost estimates would be significantly greater if meteorological conditions were different. For example, a higher wind

[38] Chanin and Murfin, 1996. *See* spreadsheets accompanying report, available online at http://ttd.sandia.gov/risk/econ.htm

speed or more stable atmospheric conditions would have contributed to a greater downwind dispersal and, consequently, greater contaminated areas.

It is important to note that the Chanin and Murfin cost estimates are based on assumed urban land use characteristics and population density. However, many of the costs associated with decontamination are "fixed," not influenced by population density. For example, demolition and restoration costs are relatively independent of population density, as are decontamination costs for streets and sidewalks. Nonetheless, the cost estimates for such population density-dependent expenses as relocation and decontamination of personal property will be underestimates when used to predict costs associated with an accident in Baltimore. The Chanin and Murfin study assume an urban population density of 1,344 persons/km^2, about 1/3rd the average population density of Baltimore (approximately 3,900 persons/km^2 in 1990). However, because the majority of costs will be "fixed" with respect to population density, we have not factored population density into an adjustment of the estimates made in Table 2.

Conclusion

This study has estimated the potential health and economic consequences of an accident similar to the recent Howard Street Tunnel fire in downtown Baltimore, assuming the accident also contained a single cask of spent nuclear fuel. The hot, long-duration fire inside the tunnel were likely sufficient to cause a release of radioactive particulates and gas into the atmosphere, contaminating a large area downwind. For our analysis, we have assumed that the accident conditions were severe enough to have caused the largest release considered in the draft EIS for the Yucca Mountain facility.

This study shows the potential devastation that could occur as a result of a release of radioactive material from a transportation accident in a large city. The potential health and economic consequences are presented, separately, in order to give some indication of the tradeoff likely to take place between preventing future health effects and expending large amount of money to properly remediate a large area. This report says nothing of the potential stigma effects that would undoubtedly result from an accident resulting in the radioactive contamination of a major portion of Baltimore, including the locations of its professional sports arenas.

These effects, though real and likely more economically devastating than the costs estimated for this report, are difficult to quantify. Regardless, this report shows that an accident involving a release of radioactive material from a transportation container could be devastating.

Appendix
Discussion of Cesium Release Fraction

When fuel is heated in reactors, a percentage of volatile radionuclides, such as cesium, will migrate out of the fuel matrix under the influence of temperature gradients and concentrate in the fuel-clad gap.[39] This "gap cesium" inventory is directly related to the release fraction in the event of an accident because it can be released in the event of any cladding breach. In fact, virtually all of the cesium released from the fuel in the event of a spent fuel shipping accident will be this "gap cesium." For the fuel matrix, the Modal Study assumes 0.3% of the cask inventory of cesium will be present between the cladding and the fuel pellet.[40] We believe that the estimate made by Gray et al (9.9% gap cesium inventory) is on more solid experimental ground. Assuming the cesium release fraction is directly proportional to the gap inventory, we intend to increase the release fraction posited in the Modal Study by a factor of 33. For particulates and gases, other release fractions apply, resulting in the following release estimates.

Table A- : Comparison of Release Fractions

	Release Estimates	
	Category 6	
Radionuclide Class	**YMEIS**	**State of Nevada**
Inert gas	6.30E-01	6.30E-01
Iodine	4.30E-02	4.30E-02
Cesium	2.00E-03	6.60E-02
Ruthenium	4.80E-04	4.80E-04
Particulates	2.00E-05	2.00E-05
CRUD	1.00E+00	1.00E+00

This significantly affects the amount of cesium which is assumed to be released in the event of an accident. Table A-2 compares the radioactive inventory of cesium, and the amount released from the spent

[39] Gray and Wilson, *Spent Fuel Dissolution Studies, FY1994 to 1994*. Pacific Northwest Laboratories. PNL-10540, 1995.

[40] The Modal Study uses the results of experiments recorded in : SAND90-2406, 1992. Sanders et al. *A Method for Determining the Spent Fuel Contribution to Transport Cask Containment Requirements.* Sandia National Laboratories.

fuel cask, using the release fractions from the Yucca Mountain DEIS and the updated cesium release fraction used in this study.

Table A- : Comparison of Cesium Release Amounts for Category 6 Accident Scenarios

	Inventory (Ci)*	Amount Released from cask, Yucca Mountain DEIS (Ci)**	Amount Released from cask, State of Nevada (Ci)**
Cs-134	7.71E+04	1.54E+02	5.09E+03
Cs-137	1.03E+06	2.06E+03	6.80E+04

*The inventory assumes 10-year PWR fuel typical of that used at the Calvert Cliffs reactor.

**Note: the amount released is from the cask; for this study, we assumed 50% of all released material would plate out on the tunnel surfaces and would therefore not contribute to the downwind plume.

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